

BOTDR Distributed Fibre Optic Strain Sensing for the Monitoring of an Existing Cast Iron Tunnel

C.Y. Gue^{1*}, M. Wilcock², M.M. Alhaddad³, M.Z.E.B. Elshafie⁴, K. Soga⁵, R.J. Mair⁶

¹ Schofield Centre, University of Cambridge, Cambridge, CB3 0EL, United Kingdom

^{2,3,4,5,6} Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ, United Kingdom

*E-mail: cyg20@cam.ac.uk

ABSTRACT: Constructing tunnels in highly congested urban cities is a challenge, as the construction will inevitably take place in close proximity to existing structures both above and below ground. As more tunnels are being constructed, it is inevitable that some tunnels will be constructed in close proximity to existing tunnels and monitoring of the existing tunnels in this case is paramount for the design and construction works. The discrete nature of conventional monitoring instrumentation requires significant interpolation and judgement in order to understand the overall behaviour of the tunnel itself. Subsequently, conservative design approaches will have to be adopted to cater for the gaps in knowledge, which could lead to unnecessary delays and high costs. Distributed fibre optic strain sensing systems based on Brillouin Optical Time Domain Reflectometry (BOTDR) could offer an alternative; in this paper a case study is presented where fibre optic cables were deployed to monitor the response of the cast iron Royal Mail tunnel in the vicinity of London Liverpool Street Station during the construction of Crossrail's new platform tunnel directly below it. Single mode single core tight-buffered cables were attached directly to the intrados of the cast iron tunnel lining of the Royal Mail tunnel to understand its response during the construction works. This paper focuses on the challenges and considerations in deploying the fibre optic system in the tunnel and presents some of the data, which demonstrates the potential benefit of using such a system in real, complex tunnelling scenarios.

KEYWORDS: BOTDR, tunnel under existing tunnel, distributed monitoring

1 INTRODUCTION

The success of tunnel construction does not solely concern the design of the tunnels themselves with linings that are capable of resisting forces subjected to the tunnels through their lifetime; it also encompasses the ability to predict and control any adverse effects on adjacent existing structures^[10].

Advancement in tunnelling methods such as earth pressure balance and slurry shield tunnel boring machines has allowed tunnels to be constructed safely in complex ground conditions. As for the tunnel linings, numerous analytical models^[3, 8, 12] as well as numerical methods have been developed over the years, which have enabled stresses in tunnel linings to be estimated. By incorporating moderately conservative parameters, the structural design of these linings can be carried out with a high degree of confidence. However, the effects of tunnelling on adjacent structures are less well understood. In an urban environment where complicated underground networks exist, constructing a new tunnel below an existing tunnel is an increasingly important problem. Limited knowledge of the response of the existing tunnel warrants higher conservatism and strict trigger limits to be specified in the design stage, which

increases the cost and schedule of construction.

Monitoring is therefore a requirement to validate the design assumptions and to provide feedback to improve the understanding of the existing tunnel's response. Conventional monitoring methods are only capable of providing discrete point measurements; while this may be sufficient for monitoring in terms of pre-determined trigger levels, the discrete nature of the data is less helpful in understanding the existing tunnel's full response.

Fibre optic strain sensing systems based on Brillouin Optical Time Domain Reflectometry (BOTDR) enable a distributed strain profile to be measured along the entire length of one single cable^[6, 7] and hence providing significantly more detailed information about the tunnel to which it is attached. The case study presented in this paper demonstrates the use of such a system in the Royal Mail tunnel in London.

2 Background

2.1 Crossrail and Royal Mail Tunnel

Crossrail is currently the largest tunnel construction project in Europe which aims to increase the capacity of London's rail by 10%, linking Reading and Heathrow in

the east and Shenfield and Abbey Woods in the west of London. It consists of 118 km of rail of which 42 km are underground tunnels in central London, serving 40 stations.

At London Liverpool Street Station, a new 11 m diameter platform tunnel of Crossrail has been constructed directly beneath the Royal Mail tunnel (highlighted in Figure 1) in a parallel alignment via open face shotcrete tunnelling method. The clear separation between the invert of the Royal Mail tunnel and the crown of the new Crossrail tunnel is only 2m.

The construction of the Royal Mail tunnel was completed in 1917 to convey mail from eastern to western sorting offices in London. Constructed wholly in London Clay at an average depth of 27 m below ground level, the Royal Mail tunnel is made of 7 grey cast iron segments, approximately 0.5 m wide, forming a 2.97 m external diameter ring. It stretches for 10.5 km, with 8 stations. In 2003 due to high running costs, the Royal Mail tunnel was closed and remains disused.

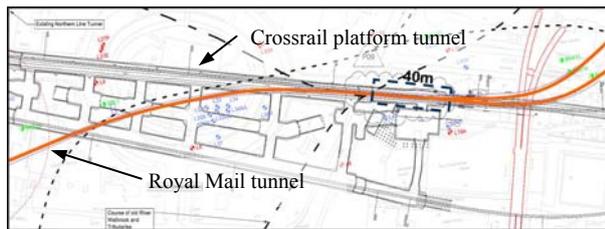


Figure 1: Alignment of Royal Mail tunnel and Crossrail platform tunnel at London Liverpool Street Station.

Since the Royal Mail tunnel is disused, it proved to be the ideal trial site for various state-of-the-art monitoring systems. This paper focuses on the fibre optics monitoring system, but some data from other advanced technologies is shown for comparison.

2.2 Principles of Operation of Brillouin Optical Time Domain Reflectometry (BOTDR)

Single mode fibre optic cables allow passage of light through its cables and while most of the signal will travel through it, some will be reflected back to the source as backscattered light. This can occur through several scattering processes. Within the Brillouin scattering process, the backscattered light will be subjected to a frequency shift, which is linearly proportional to strain. BOTDR analyser is able to detect these frequency shifts and by measuring the return time of the signal, the magnitude of strain and location can be determined [6, 7] effectively turning the entire fibre optic cable into a distributed strain sensor.

3 Installation Considerations

This section discusses some fundamental installation requirements and considerations, which need to be addressed prior to installation. Additional suggestions based on the authors' experience in this installation have also been incorporated. It is important to note that the items listed here are by no means exhaustive and attention should be given to any specific site requirements.

3.1 Measuring System (BOTDR or BOTDA)

BOTDR analyser relies on a pump laser to generate the incident light signal through the fibre optic cables. In order to obtain a clear signal, the power of the pump laser needs to be sufficiently strong. Since the fibre is only subjected to a single light source, only single access to the ends of the cable is necessary.

Brillouin Optical Time Domain Analyses (BOTDA), on the other hand, works through stimulated Brillouin scattering. Similar to BOTDR, a pulse signal is generated at one end of the cable but another continuous wave signal is emitted from the other end. Therefore, BOTDA requires access to both ends of the cable. This result in a much higher signal to noise ratio, enabling low powered pump lasers to be used [4].

BOTDA requires an extension fibre optic cable which should at least be equal to the length of the sensor (the length which is attached to the structure for strain measurement) as it receives signals from half of the entire cable loop. In contrast to BOTDR, BOTDA can take measurements at a higher rate with generally higher accuracy.

Despite the advantages of using BOTDA, the requirement for a complete measurement loop (from the analyser to the sensing cable and back to the analyser again) to exit is hard to achieve on site. In the likely event that the fibre optic cable is broken, BOTDA would not get any measurement at all while BOTDR would still be able to get the complete strain profile by measuring the strains from both ends, provided there is only a single breakage. The construction environment is difficult to control, thus damage to cables are a likely event, given the fragile properties of the cable. Therefore BOTDR was selected for reliability. It is also important to note that the Yokogawa AQ8603 analyser can achieve an accuracy of $\pm 30 \mu\epsilon$, which was deemed to be sufficient to identify the deformation mechanisms.

3.2 Survivability of Fibre Optic Cable

The fibre optic core measures less than 125 μm in diameter and is extremely fragile on its own. In order to increase its survivability, these cores are usually coated with different layers and covered with thick jackets for added protection. The level of protection will depend on the associated risks in the environment which the cable

is subjected to; fibres which will be cast in concrete would need much more protection than cables which will be fixed on the surface of existing structures.

A higher degree of protection would result in a stiffer cable and this would need to be in line with the installation methods as prestressing of stiff cables can generate high forces at anchoring points. The fibre optic cables that were used for the Royal Mail tunnel instrumentation are shown in Figure 2.

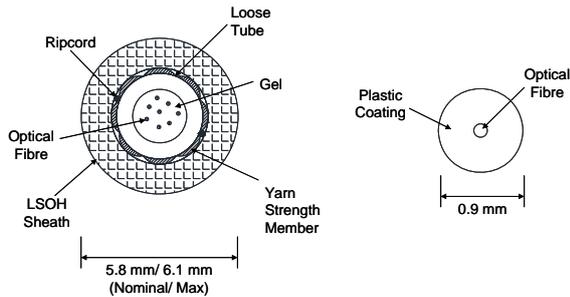


Figure 2: (Left) Excel 8C 9/125 Loose Tube LSOH cable for temperature sensing. (Right) Hitachi single mode single core tight buffered fibre optic cable for strain sensing.

3.3 Method of Installation and Cable Prestressing

3.3.1 Adhesion Methods and Requirements

In order to capitalise on the distributed strain sensing capabilities of fibre optic cables, it is favourable to employ the continuous gluing method where the cable is adhered to the lining throughout its length with epoxy. This epoxy would need to cure rapidly while achieving a high tensile and shear strength to prevent cable slippage. Araldite 2021 was used for this particular field installation and the continuous gluing method was used for all cross sectional cables.

Spot gluing was used to install the longitudinal cables along the crown of the tunnel as the presence of flanges prohibits a direct line of sight from the panels.

3.3.2 Longitudinal Cable Layout

Longitudinal response of the Royal Mail tunnel could be either of the bending or shear mode deformation ^[1] (Refer to Figure 3). The presence of the flange and existing electrical conduits along the crown meant that the fibre optic cables would have to be raised to clear the obstacles while maintaining a relatively straight line of sight.

A series of 110 mm (H) X 50 mm (W) X 80 mm (L) X 10 mm thick L brackets were bolted in the middle of each pan along the crown of the tunnel as a raised platform for the fibre optic cables. The cables were then prestrained prior to being glued on the width of the bracket with Araldite 2021.

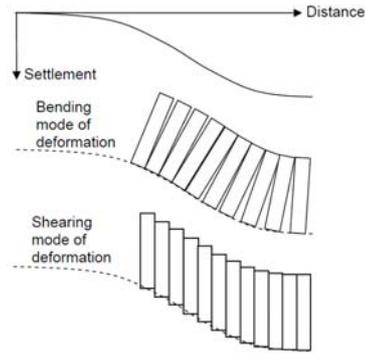


Figure 3: Bending and shear deformation modes for the existing cast iron lining tunnel in the longitudinal direction. (after Alhaddad et al, 2014)

Anchorage was provided by a Fujikura IC-Rock clamp which was rigidly attached to a shorter L-bracket to maintain the vertical alignment of cable. The procedure of prestressing is shown in Figure 4.

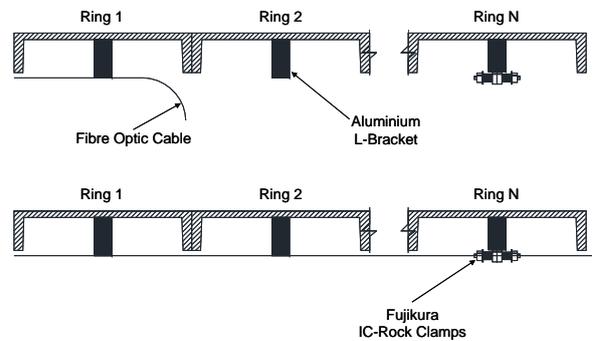


Figure 4: Procedure of prestressing fibre optic cables along the crown of existing tunnel.

In the bending mode deformation, the crown of the tunnel could be subjected to tensile strains (two adjacent rings opening up) as well as compressive strains (compression of adjacent rings) depending on whether the ring is in a hogging or sagging. As the longitudinal cables are effectively spot glued, compressive strains can only be measured as a reduction in tensile strains since the cable will need to be taut.

This would require an initial prestrain to be given to the cables which must surpass the maximum anticipated compressive strains. For simplicity, a prestrain of approximately 1000 $\mu\epsilon$ to 2500 $\mu\epsilon$ would suffice for most applications. The precise value of the prestrain is not necessary to be known since only relative strains are of interest.

However, it is important to note that for very high prestrains, the stress-strain relationship of the cables may not be linear and the sudden transition from low to high strain may cause a spike in the strain readings. Therefore it is advisable to keep the prestrain values as low as possible. Moreover, a lower prestrain value would require a lower force to be applied and

subsequently lower stresses and negligible movements or rotations of the L-brackets.

For the reasons mentioned above, Hitachi single mode single core tight buffered cable was used as the strain sensing cable as it has the lowest cable stiffness at 10 N/ %ε. Although the cable has very low stiffness, it comes at a cost of durability. It was concluded that the site posed low risk to the cables as it was a disused tunnel where the only works carried out in it is manual surveying. This justified the sacrifice in robustness to ensure minimal disturbing forces on the L-brackets.

With such an extendable cable, it becomes important to quantify the amount of strains required to keep the cable taut as the prestrain range can be easily exceeded. With the unit weight of the cable known, the maximum allowable sag can be calculated from statics to acquire an optimum installation span; defined by the distance from the L-bracket of Ring 1 to Ring N as shown in Figure 4. Installation spans should be kept as small as practicable to reduce the induced strain for a specific amount of sag.

In an ideal scenario, the linings would all be exactly level for a perfectly horizontal cable alignment across the crown. However, the reality is that the position of adjacent rings could well be different. Therefore, it is important to keep in mind that the measured sag is only indicative and may not be accurate. For the best consistency in applying prestrain, a spring balance can be used to apply consistent tensile force for the cable. Nonetheless, the practicality of this method must be weighed against the accuracy of prestrain required. As a whole, it is strongly recommended to keep the installation span as short as possible, to ensure minimal effects of misalignment of panels and cable sag.

3.3.3 Cross Sectional Cables

Tunnelling beneath the Royal Mail tunnel causes stress relief and ground deformations at the invert. This induces the lining to deform or ovalise in cross-section. To measure these strains, the cable was glued continuously along the circumferential flange (see Figure 5).

Prior to gluing, the surfaces on the flange would need to be cleaned from calcium precipitate collected from ground water intrusion over the years as well as from dirt and grease. It was found that most of the calcium precipitate could be broken off by light tapping with a hammer.

Low strength magnets were used to seat the cable on the cast iron lining while the epoxy is being applied and cured. In this scenario, a light and flexible cable such as the Hitachi cable proves to be advantageous as the magnets are capable of maintaining the curvature of the cable along the flanges.

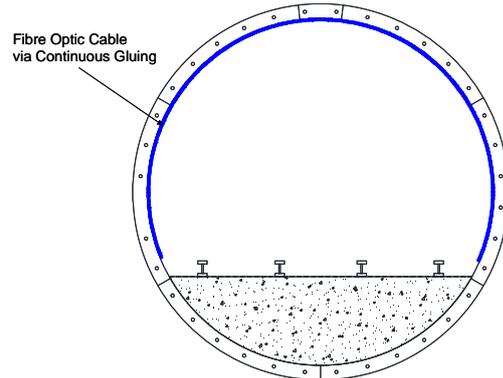


Figure 5: Cross sectional fibre optic cable attachment via continuous gluing with Araldite 2021 epoxy.

In comparison with the longitudinal section, a prestrain is not required for a continuously glued section. This is due to the fact that the cable is restrained from buckling by the epoxy as a compressive strain is applied, thus deforming an equal amount as the structural lining itself.

While no prestrain is given to the fibre optic cables in this case, installing the cables along the arc of the tunnel lining will create some tensile strains which assist greatly to identify the location of each cross section in the data analyses. For the entire system to be a closed loop, each cross sections runs freely along the side of the tunnel, unattached to the lining. The idea is to create a zero mechanical strain length which can be used for cross checking temperature strains.

Unwanted movements may occur in the free running cable as it can be dragged and moved during installation (e.g. dragged along by the movement of power cables for work lights); it is therefore recommended to provide a 5m loop of cable in an enclosure to isolate it from any movements.

3.4 Temperature Compensation

The aim of the fibre optic instrumentation is to quantify the amount of strains the Royal Mail tunnel is subjected to from the construction of the platform tunnel. Therefore, the relative strains, rather than absolute strains are of main concern.

Strain measured by the analyser is a combination of mechanical strain and thermal strain. Therefore, it is important to separate one from the other and this can only be done through the presence of a separate cable which is unattached to the lining, running along the strain sensing cables, thus subjected to the same temperature variations.

Excel 8C 9/125 loose tube fibre optic cables were used as temperature sensing cables. This cable consists of 8 fibre optic cores which are suspended in a gel filled core, as shown in Figure 2. This breaks the mechanical bond between the outer jacket and the fibre optic cores; hence strains measured would due solely to temperature.

This can then be used to offset the relative strains measured from the strain cable during analyses.

3.5 Location of Analyser and Requirements

One of the challenges in tunnel instrumentation is the lack of electrical power points. Fibre optics has the edge because it is an optical system. An extension cable can be routed (up to 10km) from the location of monitoring to a point where there is convenient power source for the analyser.

For a continuous monitoring project, it is important to use a power source that is reliable (i.e. not powered by a generator or from lines which are prone to power outages). Whenever possible, a back up power system, albeit a simple one such as that of an Uninterruptible Power Supply (UPS) should be used.

Other than being safe and secure, the analyser also needs to be secure from accidental damage and sheltered from weather and dust while being ventilated for cooling. These requirements can be met by securing the analyser inside a weatherproof strongbox with filtered ventilation.

3.6 Overall Layout

Fibre optic instrumentation layout in the Royal Mail tunnel is as shown in Figure 6. It consists of a 40 m long longitudinal section with 5 cross sections at 10 m interval. The fibre optic cable is extended via temperature cables; and for added robustness, to the top of the access shaft. All splices were kept in an enclosed splice holder. This paper presents some of the data from the longitudinal fibre optic instrumentation only.

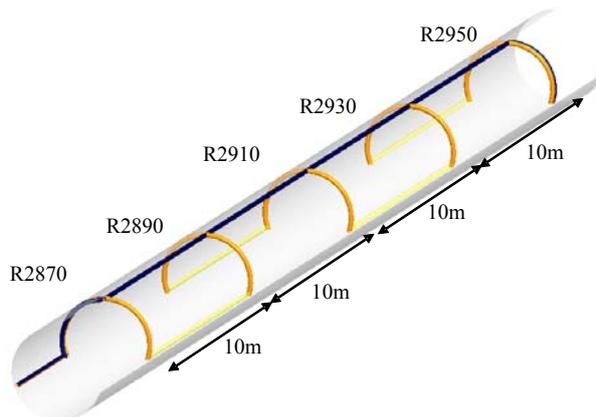


Figure 6: Fibre optic cable instrumentation layout at Royal Mail tunnel.

4 Data Analyses

Longitudinally, greenfield surface ground movements due to tunnelling follow a cumulative normal distribution curve [2, 9]. This “bow wave” movement behaviour (i.e. hogging and sagging

deformation) is expected to be transferred to the Royal Mail tunnel. Strains (relative) from a typical point in the longitudinal section between two adjacent cross sections are presented in Figure 7.

It can be seen that the fibre optics cable was sufficiently sensitive to pick up the bending mode deformations; the change in strains is obtained for the pilot tunnel construction and the final enlargement. Hogging mode is observed followed by sagging. These movements were also in line with trends of crown settlement measured by automated total stations, which gives the overall settlement behaviour. The fibre optic strain data, on the other hand gives the relative movement in terms of bending, which is related to the distortion of the tunnel.

Interestingly, the longitudinal bending mode strains inferred from the fibre optics recover almost completely for the pilot and to approximately 30% of the residual compressive strains remaining for the tunnel enlargement. The engineering implications of these residual strains require further investigation.

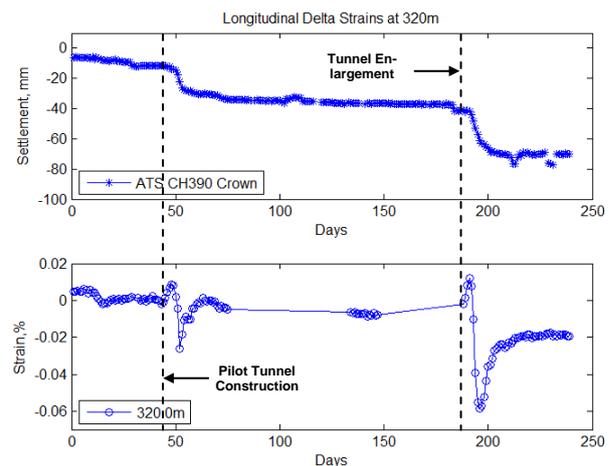


Figure 7: Comparison of Automated Total Station (ATS) crown measurements and fibre optic strain (relative) data.

By assuming a linear strain distribution from the level of the L-brackets, the extreme fibre strains of the cast iron lining extrados were back calculated from fibre optic measurements taken during construction of the pilot tunnel. A comparison was made with the theoretical greenfield horizontal strains at the crown level based on Attewell & Woodman’s equations [2]. Both the theoretical and measured strains are plotted to normalised distance as shown in Figure 8. The trough width parameter, K, was calculated via Mair et al’s equation [5] for the level of the crown of Royal Mail tunnel while the volume loss was assumed to be the designed value of 1.5%. Negative y/D indicates that the tunnel face lies ahead of the point of strain measurement, where y denotes the longitudinal distance from the tunnel face to the measurement point and D is the

diameter of the pilot tunnel.

The general trends from both the measured and theoretical strains agree very well. This indicates that the deformations of the Royal Mail tunnel were comparable to greenfield settlements, despite what might be expected to be a higher stiffness of the cast iron lining relative to the London Clay.

Similar settlement trends were recorded previously for the existing Bakerloo and Northern lines at Waterloo Station during the construction of the Jubilee Line Extension tunnels^[11]. JLE tunnels were constructed at a near perpendicular alignment below the two existing lines. Precise levelling measurements were taken from a point in the existing tunnel which was closest to the axis of JLE advancing face. It was found that these readings measured from Bakerloo and Northern lines were in agreement with the greenfield cumulative probability function curves. This supports the idea that the structural stiffness of the existing tunnel would only have minor influence on the settlement profiles; hence it will behave relatively flexibly.

Two idealised deformation mechanisms were considered by the engineers, namely bending and shear mode deformation. Where they would settle in relation to each other, the shear mode deformation is predominant. On the other hand, should the bolts have provided full restraint for the tunnel to behave continuously, adjacent rings will only rotate relative to each other in the bending mode.

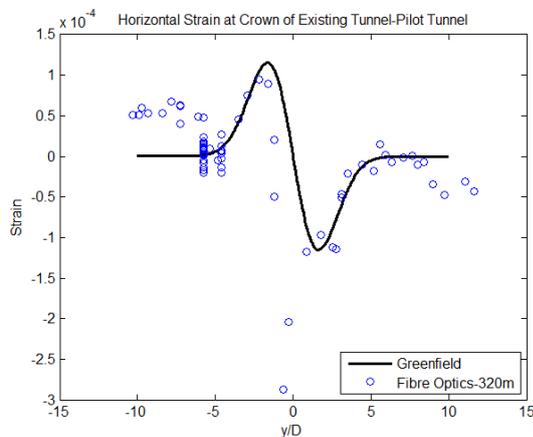


Figure 8: Comparison of strains at lining extrados based on greenfield and fibre optic measurements-Pilot tunnel construction.

Of the two idealised deformation modes depicted in Figure 3, deformation by the pure shear mode is less likely to occur. The lack of restraints provided by the bolts would allow lining rings to rotate as well as settle vertically. Thus, a coupled partial shear and bending mode deformation is more conceivable.

Shear displacement and joint opening readings were captured from wireless linear potentiometric displacement transducers (LPDT), shown in Figure 9.

Shear LPDTs measure the relative shear displacements between two adjacent rings where negative values indicate settlement of the ring nearer to the advancing face. As for bending LPDT readings, hogging mode is interpreted as the relative increase in the joint opening movement and vice versa for sagging.

In line with the fibre optics data, bending LPDT readings show that the Royal Mail tunnel undergoes hogging mode initially before changing into sagging mode as the tunnel advancing face progresses beyond the point of measurement. This trend is also observed for the shear displacements. While the result suggests that both bending and shearing movements occurred simultaneously, shearing mode was consistently predominant throughout the two construction phases. Full tunnel enlargement resulted in significantly higher shear displacement and joint movements as expected.

In a pure bending mode deformation, the shear LPDTs would not have picked up any appreciable readings and the reverse is true in a pure bending deformation. What is seen here is a compound movement of both bending and shear (gapping and differential vertical) movement consistent with a partial shear and bending mode hypothesis. It is notable that a relative residual compressive stress condition is seen following the tunnelling works. There is good agreement with the type and timeframe of movements detected by both Fibre Optics and LPDT's. However, the data in Figure 9 is currently being analysed and the instruments calibrated so it should be treated with caution.

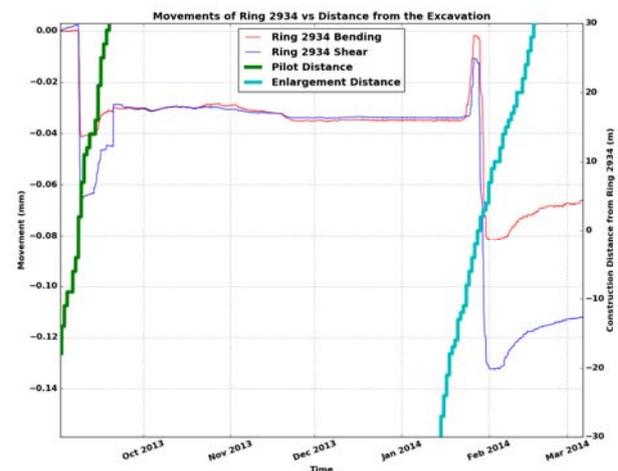


Figure 9: LPDT bending and shearing response of a single circumferential connection due to pilot and enlargement stage tunnelling.

5 CONCLUSIONS

BOTDR instrumentation has enabled a continuous strain profile of the tunnel to be measured, allowing a clear deformation pattern to be observed at each incremental construction stage. Much care and consideration is necessary to account for the practical

issues of installation as well as data analyses to obtain meaningful strain readings.

The trend of longitudinal strains matched very well with the crown settlements measured from Automated Total Station. While the effects were short lived and partially recovered when the tunnel construction influence zone has passed, the existing tunnel is still vulnerable to damage if the strains are beyond the elastic range of the lining. Initial data plots suggest that the existing Royal Mail tunnel deformed as a combination of both bending and shear mode as a result of loose circumferential bolt connections. This has allowed the tunnel to have shear displacements and rotation, with the tunnel closely following the longitudinal greenfield subsurface settlement profile. Analyses are still being carried out to confirm the modes of deformation.

Further analyses and research are currently ongoing at University of Cambridge to study the behaviour of existing tunnels when subjected to tunnelling directly beneath it in close proximity.

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